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Some factors affecting time reversal signal reconstruction

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Abstract

Time reversal (TR) ultrasonic signal processing is now broadly used in a variety of applications, and also in NDE/NDT field. TR processing is used e.g. for S/N ratio enhancement, reciprocal transducer calibration, location, identification, and reconstruction of unknown sources, etc. TR procedure in con-junction with nonlinear elastic wave spectroscopy NEWS is also useful for sensitive detection of defects (nonlinearity presence). To enlarge possibilities of acoustic emission (AE) method, we proposed the use of TR signal reconstruction ability for detected AE signals transfer from a structure with AE source onto a similar remote model of the structure (real or numerical), which allows easier source analysis under laboratory conditions. Though the TR signal reconstruction is robust regarding the system variations, some small differences and changes influence space-time TR focus and reconstruction quality. Experiments were performed on metallic parts of both simple and complicated geometry to examine effects of small changes of temperature or configuration (body shape, dimensions, transducers placement, etc.) on TR reconstruction quality. Results of experiments are discussed in this paper. Considering mathematical similarity between TR and Coda Wave Interferometry (CWI), prediction of signal reconstruction quality was possible using only the direct propagation. The results show how some factors like temperature or stress changes may deteriorate the TR reconstruction quality. It is also shown that sometimes the reconstruction quality is not enhanced using longer TR signal (S/N ratio may decrease).

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*Keywords:*nondestructive testing;time reversal signal processing; ultrasonic source reconstruction; acoustic emission; coda wave interferometry

1. Introduction

Reliable localization and identification of acoustic emission (AE) sources on complex or hardly accessible structures is often difficult problem in AE testing. Under some conditions it can be better and more precisely analysed using Time

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Reversal (TR) procedure to transfer detected AE signals onto a real or computer model of the tested structure (Prevorovsky et al. 2014). In section 2, a theoretical background of TR procedure under "non-stationary" conditions is presented. The term "non-stationary TR" covers situations where the tested sample or its surrounding experience changes in between forward and backpropagation part of TR, and also transferring of signals from one sample to another or from experiment to computer model and vice versa. It is shown that the output of time reversal experiment can be predicted by comparing forward propagating signals. The link between time reversal and Coda Wave Interferometry (CWI) is established. In section 3, some examples of non-stationary TR experiments are presented, including effects of temperature and shape variation.

2. Understanding Time reversal through signal correlation

A typical time reversal experiment (TR) is accomplished in two steps called forward and back propagation. During forward propagation the medium is excited by a source $s(t)$ and the response $u_j(t)$ is recorded by a set of j receivers in different locations. In the following back propagation, the response signals are time reversed and rebroadcast into the medium. This results in elastic wave energy focusing at the original source location and in the reconstruction of source function (Fink et al. 2000). A problem arises when the medium changes some of its properties in between both steps.

In order to describe a TR experiment under non-stationary conditions, it is useful to show the link between TR and Coda Wave Interferometry method and cross correlation in general (Snieder 2006). The result of forward propagation can be written as

$$u(t)=g_{ij}(t)*s(t)\,, \tag{1}$$

where $g_{ij}(t)$ is the Green function between the source and the receiver (the influence of transducer impulse responses can be neglected within the scope of this article). The result of backpropagation follows

$$w(t)=g_{ji}(t)*u(T-t)=g_{ji}(t)*g_{ij}(T-t)*s(T-t)\approx s(T-t)\,, \tag{2}$$

where T is the duration of time reversed signal and widely accepted approximation $g_{ji}(t)*g_{ij}(T-t)\approx\delta(t)$ is used. The result is time reversed reconstruction of the original source function at focal time T. The autocorrelation of forward propagation signal

$$x(t)=u(t)\otimes u(t)=w(t)*s(t) \tag{3}$$

is mathematically almost identical to the result of TR focusing except that in focal time we receive the autocorrelation of original source function $u(t)\otimes u(t)$. Nevertheless the fundamentals of wave propagation during time reversal described by Green functions remain unaltered in (3). It follows from the properties of autocorrelation and it has been proven in TR experiments that each part of the signal additively contributes to resulting focus. A simple dependence between focal amplitude A and signal energy can be derived

$$A=C\int_{t_0}^{t_1} u^2(\tau)d\tau\,, \tag{4}$$

where C is a constant special to the particular experimental setup, i.e. it depends on the sample, used transducers and their placement, and the source function. However, when calibrated, (4) can be used for prediction of focal amplitude of TR experiment with arbitrary long TR signals (as in fig. 1).

In previous, a stationary TR was assumed. In a non-stationary case, the Green function for backpropagation part will generally differ. The impact of this variation on TR focusing cannot be generally predicted, but the focusing performance will always diminish. Nevertheless, basic principles for typical experimental situations can be described. Conclusions from Coda Wave Interferometry (CWI) studies become extremely useful, since the close connection of TR results and correlation was already established.

Universal method of prediction of TR focusing amplitude in non-stationary case is based on additional forward propagation measurement with the same source function. The new forward propagation signal *v(t)* satisfies

$$v(t)=\tilde{g}_{ij}(t)*s(t)\ , \tag{5}$$

where the altered Green function $\tilde{g}_{ij}(t)$ is manifested and focal amplitude prediction (4) can be generalized to a scalar product of original and altered forward propagation signals

$$A=C\int_{t_0}^{t_1}u(\tau)v(\tau)d\tau\ , \tag{6}$$

Note that C remains the same as in the stationary case. The dependence in (6) holds even in stationary TR, when the backpropagated signal was manipulated (e.g. rectified for attenuation compensation). Therefore, once TR experiment is calibrated by (4), result of experiment either under altered conditions or with altered signal can be predicted. Also (6) describes signal amplitude in the original focal time T. It will be shown in case of TR with temperature variation that actual focal time may shift due to the changes in medium. In such cases usual CWI analysis using cross-correlation of corresponding intervals of u and v will determine the shift of focal time.

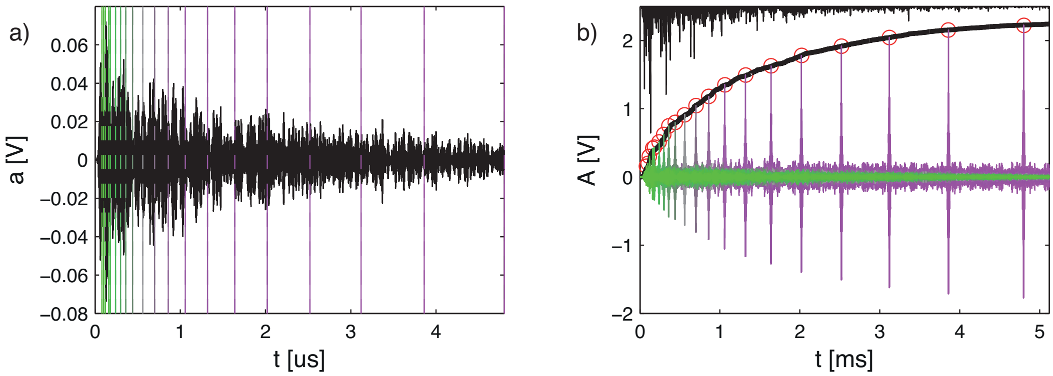

Fig. 1: (a) Intervals of forward propagation signal to be time reversed and backpropagated. (b) Results of TR focusing for 20 different signal lengths. The circles mark the focal amplitudes and the solid black line shows the prediction based on energy of forward propagation signal (4).

3. Experimental examples

To show typical results of non-stationary TR experiment a common experimental setup was used. A reciprocal TR experiment between two identical transducers (Dakel IDK-09) was performed on a simple steel block of dimensions 233 x 76 x 27 mm. An Agilent 33522A arbitrary wave generator was used for transmission and TiePie HS4 oscilloscope was used for recording of signals. A “delta function” in frequency range 50-450 kHz (computed as an autocorrelation of 10μs chirp signal in given frequency range) was used as a source. The maximum signal length was 120 ksamples at sampling frequency of 25 MHz. No preamplifiers or frequency filters were utilized. All signals were measured 16 times and averaged. Back propagation step of TR was performed with 20 signals of duration ranging from 80 μs to 4.8 ms (see fig 1a). A baseline stationary TR experiment was performed and C was calculated. Validity of (4) was verified with high precision (see fig 1b). The same procedure is repeated in following examples of non-stationary TR experiments, with shape and temperature variation using original forward propagation signal.

3.1. Time reversal with shape variation

The question regarding a shape variation is, to what extent will a small change in samples geometry (e.g. due to damage) disrupt the TR focusing. Therefore we consider a case where only a part of sample surface is modified.A localized shape change generally alters the manner how waves are propagated and reflected in the affected region, thus preventing these wave paths to contribute to TR focusing. The remaining part of unchanged surface will continue to act as a time reversal mirror until waves reflected from affected region reach it and vice versa. Therefore; with increasing propagation time deviations in the response signal will increase and no TR focusing should occur.

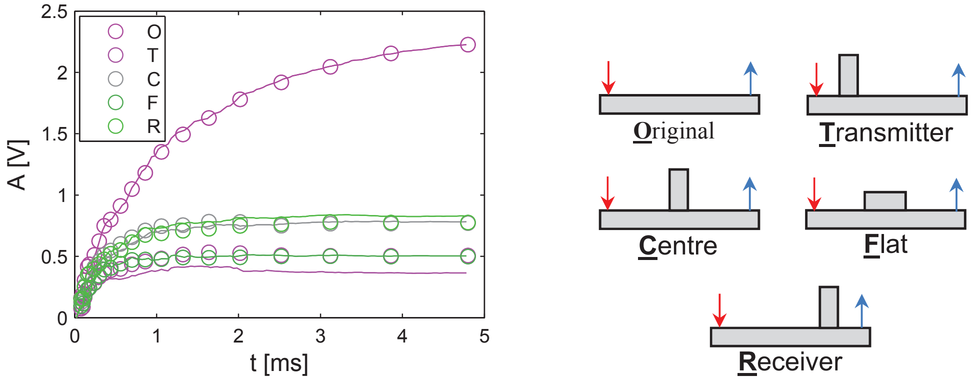

Fig. 2: Time reversal with shape variation. Focal amplitude of TR measured for 20 different signal lengths (circles) and its prediction based on forward propagation signals on original and altered samples (lines).

The effect of shape variation is demonstrated on a simple case, when a smaller steel block (62 x 60 x 27 mm) was placed in different positions onto the original sample (see schematic in fig. 2). Blocks were coupled with SonotechUltragel II which effectively prevented any reflections at the contact boundary. The results show substantial decrease in focus amplitude with respect to original focusing yet still the source reconstruction was clear within surrounding signal. Apart from stationary experiment, TR focus amplitude does not increase with longer backpropagated signals from a certain point, which is consistent with the concept outlined in previous paragraph. Altered forward propagation signals $v(t)$ were measured and focal amplitude prediction was calculated by (6). The predicted dependence of focal amplitude on backpropagated signal length shows very good agreement with actual experimental results (see fig. 2). Additionally a CWI analysis of forward propagation signals was performed and it showed that the signals become uncorrelated after approximately 1 ms (not shown here for brevity). (Michaels & Michaels 2005)

3.2. Time reversal with temperature variation

A temperature change causes thermal dilation and a change in materials elastic constants. Both effects can have a potential influence on elastic wave propagation but it was shown that the shape change due to thermal dilation can be neglected (Croxford et al. 2010). A change of wave propagation velocity causes predefined time shift of wave arrival times, which can be precisely measured by CWI. Measurements of temperature effects were performed on our reference steel block in a climatic chamber Weiss WT3. The sample was kept at fixed temperature steps (20°C, 23°C, 27.5°C, 35°C, 50°C) for at least 3 hours in order to prevent any temperature gradients within the sample. At each temperature step an altered forward propagation signal $v(t)$ as well as TR measurement was performed. Windowed CWI analysis was performed showing expected linear dependence of time delay on the signal time (fig. 3a) from which the relative velocity variation $dv/v = -0.0145\,\%/K$ was evaluated. In contrast to the shape variation, the original and altered forward propagation signals remain correlated throughout their duration but their correlation time shifts. The same applies in TR experiment, at given temperature difference the focal time will shift with the duration of the signal following the results of CWI analysis. Therefore it is possible to predict the result of TR focusing based on original forward propagation only (given that materials relative velocity variation is known). Focal amplitude can be expressed as an integral of time-shifted source function $s(t)$ weighted by energy of forward propagation signal

$$A = \max_t \left[C \int_{t_0}^{t_1} s(t-\alpha\tau) u^2(\tau) d\tau \right], \tag{7}$$

where time shift factor depends on the temperature difference as $\alpha = dv/v\,\Delta T$. Validity of (7) was supported by experimental measurements (see fig. 3b). It follows from (7) that the shape of focal amplitude dependence is defined not only by forward propagation signal but by particular source function as well, which leads to the possibility of dependence oscillations.

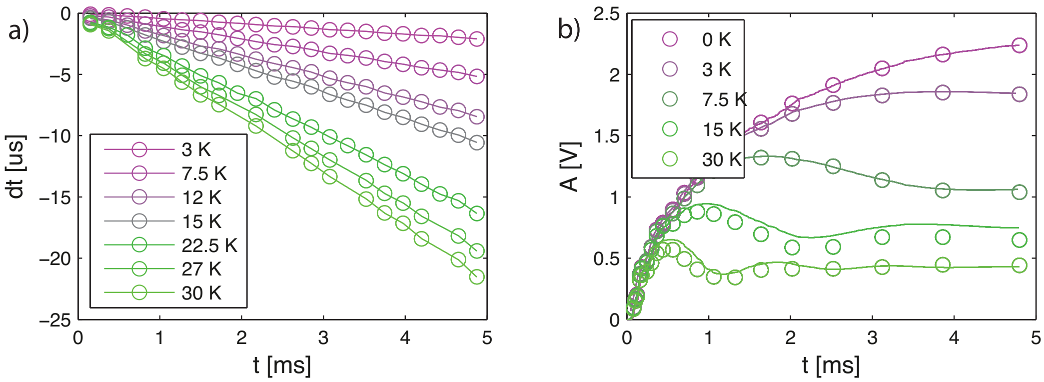

Fig. 3: (a) Results of CWI analysis on forward propagation signals. Time shift plotted against signal time. (b) Effect of temperature variation on TR experiment. Focal amplitude of TR measured for 20 different signal lengths (circles) at denoted temperature differences. The prediction based on original forward propagation signal and CWI results plotted as lines.

4. Conclusion

The effects of shape and temperature variations on TR focusing were investigated. A general theoretical approach for focusing amplitude prediction was introduced. Experimental results showed good agreement with predictions. Understanding of signal features contributing to TR focusing was possible through CWI analysis. A principal difference between shape and temperature variation influences was pointed out. In some cases, an offset between predicted and experimental values is notable, which is possibly caused by an unknown factor affecting proportionality constant *C*. Establishing link between TR and CWI is an essential tool for further development of non-stationary TR including transfer of results between experiment and simulations.

Acknowledgements

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